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Properties of an upper ocean front associated with water mass boundaries at the entrance to the Gulf of California, November 2004

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ABSTRACT

The structure of an upper ocean front at the entrance to the Gulf of California is described. The front occurred in a region of strong cyclonic shear between fresher Pacific waters, which flowed into the Gulf along Sinaloa, and salty Gulf of California waters, which flowed out of the Gulf along Baja California. Observations included two high-resolution hydrographic sections across the entrance to the Gulf. One section used a towed CTD that profiled from near surface to 125 m. A second across-Gulf section was obtained using CTDs spaced about every 10 km. Both sections indicated a nearly vertical salinity front near 108.6°W, which extended to a depth of 120 m at the northern front. The surface salinity change across the front was $\Delta S \sim 0.4$ and the width of the front 10–15 km. The surface horizontal mixing ratio, -0.15 to -0.7, indicated that salinity dominated the density change. The mixed layer was strongly developed to a depth of ~45 m. Features that were observed at the front included a surface jet (10 km wide, 0.25 m s^{-1}), subduction from the mixed layer to the top of the pycnocline, evidence of symmetric instability driven by atmospheric cooling of surface waters, and a deformation rate of -0.5×10^{-5} s^{-1}. Northward ageostrophic currents in the upper 60 m extended inflow 55 km to the west of the surface front. Immediately below the bottom of the mixed layer, the seasonal pycnocline was characterized by a 15-m thick and 50-km wide salinity maximum (minimum), S=34.9–35 (S=34.3–34.4) for the outflow (inflow). These features were not distinct in the frontal zone. Temperature flux and diffusivity were estimated to be about 7.6×10^{-2} °C m s^{-1} and 8600 m^2 s^{-1}, respectively.

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1. Introduction

The entrance to the Gulf of California (GC) marks the locus of exchange between waters of the Gulf and the adjacent Pacific Ocean (PO), which are critical for heat and salt balances in the Gulf. Here, waters from the Gulf lie adjacent to, co-mingle with, and mix with waters from the Pacific Ocean. The boundaries between the surface waters often form sharp fronts which are easily seen from space and are persistent along the continental slope as well as across the entrance to the Gulf, the latter marking where Gulf and Pacific waters meet (Belkin, 2005; Belkin and Cornillon, 2007; Belkin et al., 2009).

In late fall, large scale ocean conditions favor frontogenesis. Strong horizontal shear exists between inflowing Pacific and outflowing Gulf waters. These currents form a cyclonic circulation of narrow (20–30 km), deep flows (0.1 m s^{-1} at 1000 m) on either side of the mouth of the Gulf. They are baroclinic in structure and easily seen in high resolution (10-km) CTD sections (Roden, 1972) or direct current measurements (Collins et al., 1997). The exchanges are driven by wind and buoyancy and result in cooling and freshening of the Gulf (Castro et al., 1994; Berón-Vera and Ripa, 2000). The November exchange is marked by the transport of Tropical Surface Waters (TSW) into the Gulf (Mascarenhas et al., 2004).

Seasonal meteorological conditions also promote frontogenesis at the entrance to the Gulf in late fall. The atmosphere is generally cooler than the ocean in November and the resulting air–sea buoyancy flux contributes to deepening of the mixed layer, convective overturning and symmetric instability (Taylor and Ferrari, 2010). Although northerly winds dominate from late summer though early spring in the Gulf (Parés-Sierra et al., 2003, Marinone et al., 2003), southerly winds occur six percent of time (National Geospatial Intelligence Agency, 1994). These southerly winds provide a down front component of wind stress which transport more dense surface water toward less dense surface water, initiating vertical motions in the upper ocean including symmetric instabilities (Taylor and Ferrari, 2010).

Existing hydrographic data provide evidence of strong currents in fall and associated frontal structures. Roden (1971) studied hydrographic data from late fall of 1969 and suggested that the

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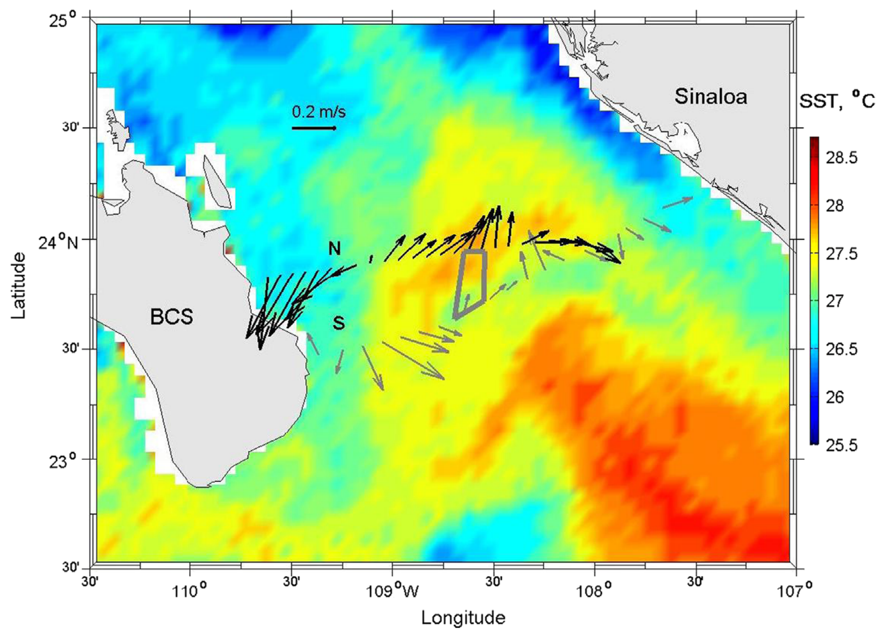

Fig. 1. AVHRR image for November 11, 2004. The color bar at the side of the chart gives the temperature scale (°C). Arrows represent near surface flow as measured by vessel mounted current profilers, 15–17 November 2004, for 0.1° longitude bins. Black arrows are from 300 kHz measurements and gray arrows from 75 kHz measurements. The trapezoid (dark-gray) indicates the frontal zone detected by continuous shipboard measurements of sea surface density and salinity.

border between TSW, California Current Water (CCW) and the Gulf of California Water (GCW) was characterized by a front consisting of a strong horizontal salinity gradient off the southwestern tip of the Baja California peninsula. Collins et al. (1997) pointed out the presence of a frontal eddy vortex in a satellite image from November 1990 that indicated a front between cold Pacific waters and either warm tropical waters or GCW at the Gulf entrance.

An example of these flow patterns is given by an AVHRR image for November 11, 2004 (Fig. 1). Surface currents measured by a vessel mounted Acoustic Doppler current profiler (VMADCP) during November 15–17, 2004, (described further below) have been superimposed in Fig. 1. Here a tongue of warm waters appeared to extend poleward along the Mexican coast into the Gulf of California. The VMADCP and AVHRR data show that the surface waters circulated cyclonically across the entrance to the Gulf, and left the Gulf along the Baja California Peninsula. Upon exiting the Gulf, the AVHRR data show a tongue of warm water extended poleward along the Pacific coast of Baja California. Pacific Ocean fronts that are suggested by this circulation pattern include boundaries (1) between the Tropical waters carried by the Mexican Coastal Current and Pacific Waters and (2) between Gulf Waters and Pacific Waters along the Pacific Coast of Baja California. Within the Gulf, a third front, the focus of the paper, was formed at the entrance to the Gulf in a region of strong horizontal shear between currents flowing into and out of the Gulf.

In November 2004, two high resolution hydrographic sections were occupied across the entrance to the Gulf (Fig. 2) that provided a detailed view of the structure of the upper ocean. Note that the entrance to the Gulf lies in Pescadero Basin, which has a northern sill depth of ~2000 m and at its southern limit freely communicates with the Pacific Ocean above 3000 m. The two sections met at the 500 m isobath near Sinaloa and were separated by 50 km at their western origins along the Baja California coast. The southern section was obtained from traditional CTD casts spaced 10 km from one another and provided a mesoscale resolving view of the upper 1000 m of the water column. The northern section was sampled continuously to a depth of about 120 m using a CTD mounted on a towed profiler and provided a higher resolution view of the small-scale (1 m vertically, 1 km horizontally) structure of the upper layer. While these sections showed a number of frontal zones, the strongest frontal zone was the one that separated in- and out-flowing waters. The location of this frontal zone is shown by the trapezoidal region along 108.5°W between the two hydrographic sections shown in Figs. 1 and 2.

The purpose of this study is to describe the properties of the upper ocean front observed at this water mass boundary in the context of regional circulation patterns and global estimates of frontal properties (Fedorov, 1986). The paper is organized in the following manner. Observations and methods are described in the second section. Results are described in the third section, proceeding from large scale to mesoscale to sea surface conditions, before smaller scale frontal features are examined in more detail. A summary of frontal conditions is given in the last section.

2. Methods

Measurements and data processing methods are described below. Continuous measurements of sea surface water properties and meteorological conditions made on both legs are described first. A description of methods used for measurements to a depth of 1000 m on the southern leg are described next, followed by details of methods used for shallow upper ocean measurements on the northern leg. The final section describes methods used to process the CTD data from both legs.

2.1. Meteorological and sea surface measurements

Meteorological and sea surface conditions were observed every 24 s while the ship was underway. Meteorological measurements (wind speed, air temperature and humidity, long and short-wave radiation) were made from the ship's mast, about 18.9 m above the sea surface. Sea surface conditions were measured using seawater which was pumped from a sea chest located in the ship's bottom at a depth of 3 m to a SeaBird 21 thermosalinograph located in a laboratory about 10 m away. The accuracy (precision) of the conductivity measurements was 0.001 (0.0001) S m^{-1}, and for temperature measurements was 0.01 (0.001) °C. Underway